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ATOMIC X-RAY SPECTRA OF ACCRETION DISK ATMOSPHERES IN THE KERR METRIC

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We calculate the atmospheric structure of an accretion disk around a Kerr black hole and obtain its X-ray spectrum, which exhibits prominent atomic transitions under certain circumstances. The gravitational and Doppler (red)shifts of the C V, C VI, O VII, O VIII, and Fe I–XXVI emission lines are observable in active galaxies. We quantify the line emissivities as a function of radius, to identify the effects of atmospheric structure, and to determine the usefulness of these lines for probing the disk energetics. The line emissivities do not always scale linearly with the incident radiative energy, as in the case of Fe XXV and Fe XXVI. Our model incorporates photoionization and thermal balance for the plasma, the hydrostatic approximation perpendicular to the plane of the disk, and general relativistic tidal forces. We include radiative recombination rates, fluorescence yields, Compton scattering, and photoelectric opacities for the most abundant elements.

1. Introduction

One of the key signatures of strong gravity in astrophysical black holes is the peculiar shape of the Fe Kα emission line observed at 6.4 keV in active galactic nuclei and black hole X-ray binaries.[1] The Fe Kα emission has been extensively studied in model calculations and Monte Carlo radiation transfer models. In such models, the Fe Kα line emission is produced by near-neutral plasma in the accretion disk that is irradiated by an external source of nonthermal X-rays and γ-rays, located somewhere above the accretion disk. The Fe Kα line is skewed and redshifted down to ~ 3 keV, but it only exhibits a small blueshift. Its line profile has been described by a raytracing model of a luminous disk in the Kerr metric.[2] The Fe

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Kα line provides evidence for an accretion disk extending very close to the event horizon of the black hole (however, alternative models exist, i.e. see Titarchuk in these proceedings). Although the origin of the nonthermal radiation bathing the disk is not fully understood, it is likely produced by inverse Compton scattering of ~ 100 keV electrons with thermal UV radiation produced by the disk.

The emission lines C VI, N VII, and O VIII Lyα have been tentatively identified in a handful of active galaxies with line profiles that are similar to that of the Fe Kα line.[3] This identification has been controversial since the same X-ray spectra can be interpreted with photoelectric absorption features produced by plasma that is known to exist several parsecs away from the black hole.[4] Our primary goal is to produce a theoretical prediction for such a recombination spectrum, accounting for relativistic effects. Since the raytrace calculation by Laor[2] omitted the physics of the line emission mechanism in the disk, it introduced a power-law emissivity $\epsilon \propto r^{-q}$ as a function of radius r, with q as a free parameter. Another purpose of our work is to test whether or not this line emissivity index q is directly related to the emissivity index of the total radiative energy of the disk, q_T, as a function of r. The Shakura & Sunyaev[5] disk model implies that $q_T = 3$, but in situations where the disk is heated by a coupling with the Kerr hole, $q_T = 3.5$.[6] However, fits to the lines observed with the *XMM-Newton* X-ray observatory show emissivity indices for Fe Kα of $q = 4.3$–5.0[7] and up to $q = 5.4 \pm 0.5$,[8] that are larger than the theoretical predictions of q_T. Could $q \neq q_T$ be due to atmospheric effects in the accretion disk? We test this hypothesis for the fluorescence and recombination X-ray lines of the most abundant elements.

2. Disk Atmosphere Structure

We will describe how we calculate the disk atmosphere structure, with the understanding that we are forced to introduce simplifying assumptions, specifically due to our ignorance of the dynamical processes responsible for electron acceleration in the atmosphere and disk corona. Underlying the atmosphere, we assume an accretion disk interior model,[5] modified by the general relativistic corrections applicable in the Kerr metric.[9] We build upon this model by calculating the ionization structure of the atmospheric interface between a fully ionized corona and the disk interior, with the atmosphere energized by external nonthermal irradiation from above and blackbody radiation from below. We do not know the relationship between the energy (per unit disk area) dissipated in the disk $U_T = U_T(r)$, the energy emitted as blackbody radiation U_{bb}, and the nonthermal radiation energy U_{nt}, so we choose $U_T = U_{bb} + U_{nt}$, and fix $U_{bb} = U_{nt}$ for all r. We also assume that the spectral index of this nonthermal radiation (which is an observable) is constant with radius, but that its low-energy cutoff is related to the local temperature of the disk interior, consistent with a Comptonization origin.

Our calculation relies on the dominance of photoionization and recombination in determining the temperature and ionization state of the plasma in the accretion disk atmosphere, since radiative heating is large compared to collisional heating. As the depth increases, the atmosphere becomes optically thick in X-rays, finally reaching a disk interior dominated by collisional heating. Discrete atmospheric layers are produced by the thermally stable phases of the photoionized plasma, as seen in Fig. 1a. The intermediate layer at temperature $T \sim 6 \times 10^5$ K, as well as the deepest layer, emit copious recombination emission in the soft X-ray band, while the Fe Kα fluorescence emission is produced only at the deepest layer, at $T \lesssim 4 \times 10^5$ K. The Thomson depth of the X-ray atmosphere decreases with radius, and the temperature of the disk interior drives the ionization of the deepest layer.

We choose model parameters applicable to an active galaxy such as MCG - 6-30-15, which shows a prominent broad Fe Kα line, and also the putative soft X-ray broad lines. We set the accretion rate to $\dot{M} = 10^{24}$ g s^{-1}, the power-law continuum photon index to $\Gamma = 2.1$, the high-energy exponential cutoff of the hard X-ray spectrum to $E_{\rm cut} = 150$ keV, the black hole mass to $M = 10^7$ M$_\odot$, and the dimensionless black hole spin to $a = 0.998$. The inner disk torque is set to a nonzero value, increasing the accretion efficiency by 0.08. We included the general relativistic correction for the tidal force in the vertical direction, but we did not include the temperature corrections (which are affected by the torque at the inner boundary in any case). We binned the accretion disk to follow the Laor[2] prescription of $r_n = 1600n^{-2}r_g$ with $n = 2, 3, ..., 36$, in $r_g = GM/c^2$ gravitational radii. The maximum number of vertical bins is 500, but 200–300 is typical.

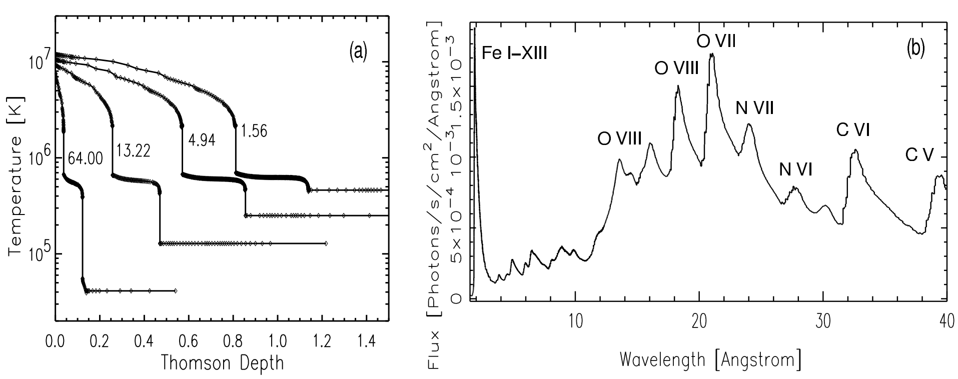

Figure 1. (a) Atmospheric temperature as a function of vertical Thomson depth. Selected radii in units of gravitational radius are shown. (b) X-ray line spectrum of the disk atmosphere at an inclination of 30°, without the continuum emission, and including most relativistic effects.

3. Disk Atmosphere Spectrum

We calculated the atomic X-ray spectrum with semi-analytic and with Monte Carlo methods (to improve the accuracy of the transfer calculation and Compton scattering). The spectra include recombination emission from the hydrogen-like and helium-like ions of C, N, O, Ne, Mg, Si, S, Ar, Ca, and Fe, plus the L-shell ions of Fe, and H and He. We use a fluorescence yield of 0.34 for all Fe ions with an M-shell electron. Fe ions with just L-shell electrons are assumed to have zero fluorescence yield, since photon trapping will suppress fluorescence. The semi-analytic X-ray spectrum shown in Fig. 1b exhibits a series of distinct sawtooth peaks, each due to a line broadened by Doppler shifts and gravitational redshift. The most prominent lines are O VIII, O VII, N VII, C VI, and C V. There is *not* a strong contribution to the emission from Fe L-shell ions, as reported by other authors.[10] The equivalent width relative to the incident continuum of O VIII Lyα is 23 eV, while that of the entire line complex, from 13 to 35 Å, is 110 eV. The latter is well within the detection limit of the *Chandra* and *XMM-Newton* X-ray observatories.

The best candidate for this kind of emission is NGC 4051, which exhibits a soft X-ray flux excess that can be fit by an O VIII line complex emitted by the inner disk.[11] However, the sawtooth profiles of the emission lines are not clear in the data. Both MCG -6-30-15 and Mrk 766 could exhibit such lines, but our Monte Carlo[12] has not yet reproduced the bright N VII line, nor the notable absence of the Lyman series and radiative recombination continua in the observed[3] spectral fits.

4. The Line Emissivities

The modeled emissivities as a function of radius of O VII, O VIII, N VII, N VI, C VI, and C V, all track the input radiative energy index q_T to within $\Delta q = \pm 0.5$. The hydrogen-like ion lines have systematically larger values of q than the helium-like ion lines. For the Fe Kα line at 6.4 keV, $q = 3.0$, unless the disk interior $T \gtrsim 4 \times 10^5$ K, in which case fluorescence is suppressed. However, for both Fe XXVI and Fe XXV Lyα lines at 6.7 keV and 6.9 keV, $q = 4.0$, which is larger than the $q_T = 3.0$ input. This steep emissivity q is due to a thickening of the hot atmosphere and an increase in density at small radii. Atmospheric effects increase the emissivity indices significantly only for Fe XXV and Fe XXVI lines. The models show that a power-law description of the line emissivities is, in general, only a rough approximation.

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